Direct Electron-Positron Pair Production by 200-GeV Negative Pions*

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We have studied direct electron-positron pair production by the collision of 200-GeV π^- mesons with a neon target. The data consist of 622 direct pairs with momenta ranging from 10 MeV/c to 7.5 GeV/c. We have measured the total production rate to an accuracy of 10% and studied the relevant momentum and electron-positron momentum partition spectra. In contrast to several recent experiments, we find excellent agreement with the predictions of quantum electrodynamic calculations.

Direct electron-positron pair production arises from the electromagnetic interaction of a charged particle with the Coulomb field of a nucleus. In principle, this process can be well calculated from quantum electrodynamics and about thirty theoretical papers have been devoted to this subject over the past forty years.[1-3] This large number of calculations attests to the fact that the technical application of quantum electrodynamics (QED) to direct pair production is complicated. In addition to straight computational details, other considerations enter such as the effects of nuclear and atomic form factors[1] and the influence of medium-dependent multiple scattering[2] which is known to suppress the soft component of bremsstrahlung.[4] The latest calculations agree fairly well, however, and prove to be relatively insensitive to model-dependent details.[3] A theoretical prediction accurate to approximately 10% should be possible over a large direct-pair-momentum range.

This expectation has been brought into some doubt recently by the results of four experiments which report large discrepancies (factors of from 2 to 10) between QED calculations and measured direct-pair-production rates. These experiments were done with nuclear emulsions and used beams of 16- and 150-GeV/c μ^- mesons[5] and 200-GeV/c protons.[6] Earlier experimental studies of direct pair production by π^- mesons have come to conflicting conclusions about their agreement theory.[7]

In this paper we present the results of a new measurement of direct pair production which has small systematic errors and twice the total number of events acquired in all previous experiments with monoenergetic particle beams. The data were obtained using the Fermi National Accelerator Laboratory's (FNAL) 30-in. bubble chamber filled with a hydrogen-neon mixture having a density of 0.255 g/cm^3 with 30.9-mole% neon content. A total of 50 000 photographs were taken with an incident 200-GeV negative-pion beam.

Direct pair production is very evident in this experiment with one event occurring about every forty photographs. A typical event has an undeflected π^- beam track with the electron and positron produced very forward and spiraling in the 25-kG magnetic field. Over 90% of the direct pairs produced in the momentum range from 10 to 1000 MeV/c have this very characteristic signature. Our scanning criteria were more general, however, to allow for unexpected production features and to extend the detected direct-pair momentum as high as possible. We recorded all three-pronged events with an undeflected beam track and two minimum ionizing tracks in the momentum range from about 1 to 5000 MeV/c. In addition, any electron-positron pairs from γ rays converting near a beam track were recorded for the purpose of evaluating the background caused by the unresolved superposition of these pairs with beam tracks. The scanning was done with a magnification of about 1.4-times lifesize and a photograph was rejected if any track other than beam tracks entered the scanning fiducial volume. This procedure resulted in the acceptance of 27 550 photographs and provided a total π^- track length of 4.01×10^6 cm useful for direct pair production in a fiducial volume 41 cm long.

Scanning efficiency studies were made as a function of the $e^\pm$ momenta p_+ and p_-, the direct-pair momentum $k=p_+ + p_-$, and the momentum partition $\mu=(p_+ - p_-)/(p_+ + p_-)$. Only the following simple cuts were found to be necessary:

$$2 < p_\pm < 5000 \text{ MeV}/c,$$

$$10 < k < 10\,000 \text{ MeV}/c.$$

Within this kinematic region the average single-

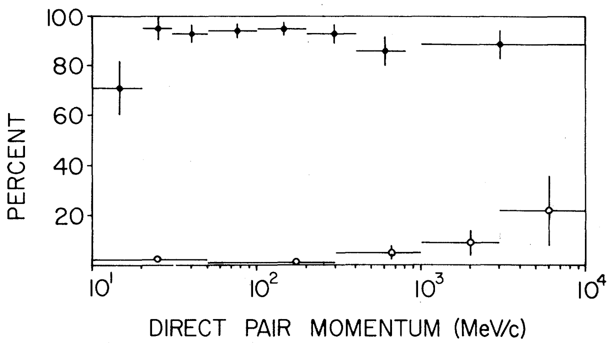

FIG. 1. Experimental corrections applied to the data as a function of direct-pair momentum. The solid circles show the single-scan efficiency and the open circles the total background subtraction.

scan efficiency was $(91.1 \pm 1.4)\%$ as determined by doubly scanning 30% of the film. The scanning efficiency varies with direct-pair momentum as shown in Fig. 1.

Contamination of the sample of direct pairs from all background sources is small and amounts to a total of $(3.0 \pm 1.0)\%$ when averaged over direct-pair momenta. The main source of background is from γ-ray pairs, converting very close to the beam track, which come both from bremsstrahlung of the π^- beam and from the forward production of π^0's. We measured this background from the distribution of the transverse distance between the beam track and converted γ-ray pairs that were collected in scanning for this purpose. Extrapolating this distribution to small transverse distances provided a measurement of the unresolved pairs occurring within 0.3 mm of the beam. All other backgrounds were found to be negligible except for a small contribution from hadron production for direct pairs with momentum from 1 to 10 GeV/c. In this momentum range, events were accepted as direct pairs if their opening angle was less than 2°. This reduced the contamination from hadron production to less than 5%.[8] The total background from all known sources is shown as a function of momentum in Fig. 1.

The momenta of the electron and positron were calculated from measurements made directly on the scan table. This procedure minimizes systematic errors at little expense to measurement precision. The results of the curvature measurements were converted to momentum and corrected properly for ionization and bremsstrahlung losses. The average direct-pair-momentum error is 8% and does not vary much with momentum.

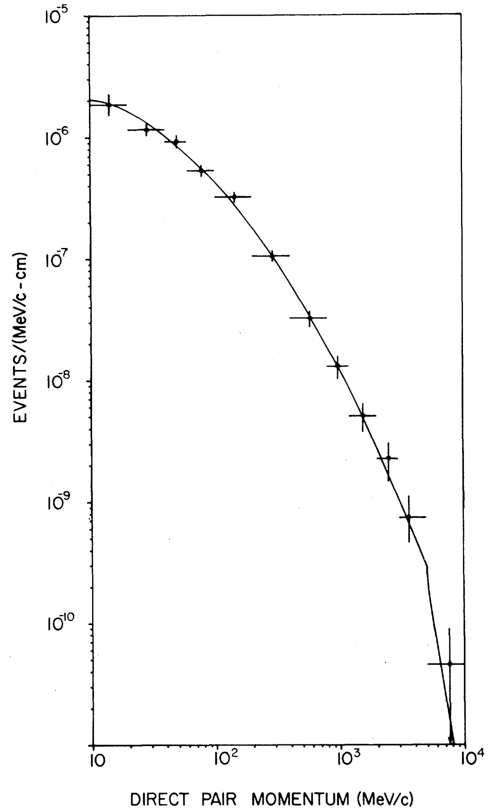

FIG. 2. The direct-pair differential-production rate versus momentum. This shows the number of direct pairs produced in a given momentum interval (horizontal bars) for 1 cm of 200-GeV π^- track length in our hydrogen-neon mixture (about 95% of the production is from neon). The curve is the theoretical prediction as calculated by Ternovskii. Our experimental cuts on the electron and positron momenta have been properly included. These produce the sharp break in the curve occurring at 5 GeV/c.

Our final sample of data consists of 622 events which represent 652 ± 31 direct pairs after all corrections. The momentum spectrum from 10 MeV/c to 10 GeV/c is shown in Fig. 2. The other differential distribution of interest is that for the energy partition μ. Figure 3 shows this folded about zero and plotted separately for direct pairs in three momentum ranges. The errors quoted include all experimental uncertainties except for an overall normalization error of 8% caused mainly by an uncertainty in the density of neon in the target.

A comparison of the data with theory involves numerous considerations that can be only briefly outlined here. Figure 4 shows the Feynman dia-

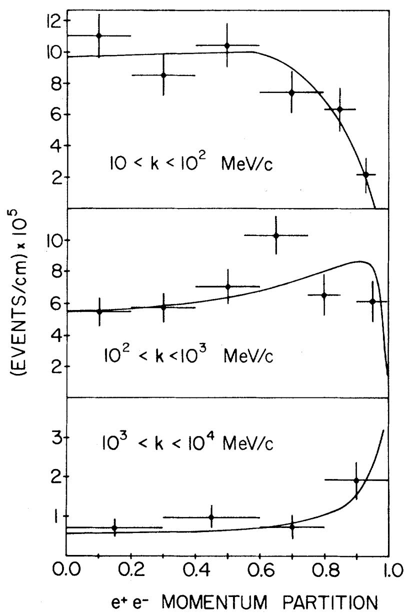

FIG. 3. The electron-positron momentum partition in three direct-pair-momentum ranges. Here we have plotted $|p_+ - p_-|/(p_+ + p_-)$. The solid curve is calculated as described in Fig. 2.

grams for the two lowest-order amplitudes contributing to direct-pair production. The bremsstrahlunglike process (a) contains not only a Coulomb interaction with the nucleus but also a nuclear diffractive part. Process (b) is purely electromagnetic. In addition, when dealing with a condensed medium, it is possible that the coherence length of the process is long enough that multiple-scattering effects from several atoms can become important. We have used calculations by Ternovskii[1,2] to examine all these effects

TABLE I. A summary of the direct-pair-production rates measured in this experiment. (Errors do not include a systematic normalization error of 8%.) The theoretical prediction is from Ternovskii's calculation with our experimental cuts included.

Direct pair momentum range (MeV/c)	Production rates Measurement (events/cm)	Theory
$10-10^2$	$(8.24 \pm 0.59) \times 10^{-5}$	8.03×10^{-5}
10^2-10^3	$(6.98 \pm 0.46) \times 10^{-5}$	6.39×10^{-5}
10^3-10^4	$(1.04 \pm 0.16) \times 10^{-5}$	0.87×10^{-5}
$10-10^4$	$(1.63 \pm 0.08) \times 10^{-4}$	1.53×10^{-4}

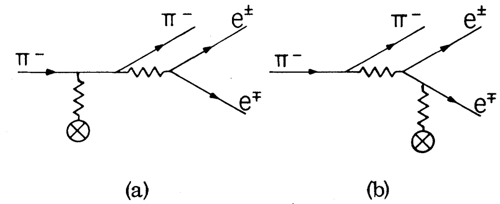

FIG. 4. Feynman diagrams representing the basic electromagnetic contributions to direct-pair production.

and find that only process (b), with no multiple scattering, is important in the momentum range of this experiment. The result of Ternovskii's calculation[1] is shown by the solid curves in Figs. 2 and 3. Table I shows a statistically more precise comparison of our data to this calculation by presenting the production rate integrated over various momentum ranges.[9] The theoretical prediction[10] is an absolute one with no free parameters[11] and is in excellent agreement with all aspects of our data.

In summary, our measurement of direct-pair production by 200-GeV π^- mesons from the Coulomb field of a neon nucleus agrees with the QED prediction to an accuracy of about 10%. At this level theoretical uncertainties of a comparable magnitude enter. It would have been unexpected to find any discrepancy in QED in the kinematic domain studied in this experiment, but our verification of technically complicated calculations is important. The agreement that we observe with the theory of direct-pair production is in contrast to large discrepancies found in recent emulsion experiments using μ^- meson[5] and proton beams.[6]

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[8]This was estimated from a study of the opening-angle distribution between the positive and negative tracks. Direct-pair production has a sharp peak at zero degrees while hadron production (with both tracks having momentum less than 5 GeV/c) occurs predominantly at large angles.

[9]The total production rate of 1.63×10^{-4} cm^{-1} corresponds to a cross section for the neon-hydrogen mixture of 4.8 mb. However, since direct-pair production is approximately proportional to Z^2, we are essentially measuring production from neon in this experiment. The cross section for direct-pair production from neon alone is 25 mb.

[10]This ignores direct-pair production from atomic electrons. We know of no calculation that properly takes this into account, but, guided by calculations done for γ-ray pair production, we estimate that this would increase the theoretical prediction by about 10%.

[11]Although there are no free parameters, Ternovskii's calculation does incorporate some model-dependent features such as using the Thomas-Fermi model to estimate the effect of electron shielding.

Production of Δ (1236) in pp Collisions at High Energies*

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We present a comparative study of inclusive Δ^{++}(1236) production in pp collisions at 102 and 400 GeV/c. To better than 10% accuracy the invariant Δ^{++}(1236) cross section does not depend on energy. A remarkable similarity is observed between the properties of the neutral-baryon system produced in association with the Δ^{++}(1236) and the known characteristics of π^-p collisions.

The characteristics of inclusive Δ(1236) production at high energies have recently been studied for pp collisions[1] at 303 GeV/c and preliminary results have been reported[2] at 205 GeV/c and at 69 GeV/c.[3] Here we present an investigation of the energy dependence and other hitherto unstudied properties of the reaction

$$p+p\rightarrow\Delta^{++}(1236)+X^0, \qquad (1)$$

where X^0 represents anything accompanying the Δ^{++}(1236).

The data are from a 33 000-picture exposure of the Fermilab 30-in. bubble chamber to 102-GeV/c protons and from a 19 000-picture exposure at 400 GeV/c.[4] In both experiments the beam transmitted to the bubble chamber had the same momentum as the extracted proton beam from the main ring and, consequently, beamlike background was negligible.

We measured all charged tracks for a sample of 3000 and 2200 events at 102 and 400 GeV/c, respectively. The procedures used for proton identification have been described elsewhere.[4,5] In this paper we will be concerned with Δ^{++}(1236) production in the backward hemisphere of the center of mass, and, consequently, to avoid biasing this sample of data through our imposed scanning criterion used to select protons, we will restrict our consideration to events which have π^+p invariant masses (M_Δ) in the 1.12- to 1.32-GeV interval and have low values for the squares of four-momentum transfer between target proton and the Δ^{++} ($|t_\Delta|<0.6$ GeV^2). With these cuts on M_Δ and t_Δ, we retain for further study of Reaction (1) 160 and 119 events at 102 and 400 GeV/c, respectively, corresponding to cross sections of 1.65 ± 0.13 and 1.59 ± 0.15 mb.

Figure 1(a) displays the π^+ mass spectrum for the selected data samples. At both beam energies, a clear enhancement is observed in the π^+p